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Research paper

Optimization of a finned concentric pipes heat exchanger for industrial recuperative burners

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HIGHLIGHTS

- A systematic method for the optimization of a double pipe heat exchanger is proposed.
- The method adopts CFD and a constrained version of the simplex optimization algorithm.
- The exchanger efficiency is optimized under different operating conditions.
- A resistance network analysis is included to address possible further improvements.
- The economic impact of the optimized solution in industrial kilns is estimated.

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ABSTRACT

A numerical application is presented in which a finned concentric pipes heat exchanger is simulated by means of CFD, and optimized by the Nelder and Mead simplex downhill optimization algorithm. The heat exchanger parameterization takes into consideration the main geometrical aspects of the exchanger under different operating conditions. The work originates from an industrial problem related to heat recovery issues in recuperative burners, in which air is pre-heated by the exhaust gas before entering the combustion chamber. Such a device allows for an *in situ* and more efficient heat recovery from exhaust gases, also reducing both the sizing of the heat recovery system downstream to the furnace, and the burner fuel consumption. It is found that the fine tuning of just a few geometrical parameters can result in a sensible enhancement of the exchanger efficiency.

1. Introduction

Heat exchangers are commonly found in industry for transferring heat between two media, and represent a widely investigated research topic. An important application is given by heat recovery in high temperature industrial systems, where the thermal powers at play are large, and so are the margins for energy efficiency improvement.

This is true when dealing with burners for industrial furnaces, and with heat recovery from high temperature exhaust gases. More in general, energy recovery and its better exploitation in high temperature industrial processes have received much attention in literature over the last few years in view of the pressing environmental issues. We thus find works addressing the recovery of pre-heated air from the cooling processes into industrial kilns [1], the exploitment of the heat loss from the mantle of a rotary kiln to pre-heat the combustion air [2], the use of low LHV syngas in adapted industrial burners [3], and kilns [4].

In traditional continuous roller kilns, such as those used for firing ceramic tiles, the burners expel the exhausts directly into the kiln room, where it is sucked by a unique intake manifold upstream by the kiln entrance, and sent to a global heat recovery system.

To better exploit the enthalpy of the exhausts, the heat recovery function can be decentralised and appointed, at least in part, to local recuperative burners. Basically, a heat exchanger is coupled to the burner and used for pre-heating the combustion air with the exhaust gas. Downstream to the burner the exhaust gas is then sent to a global heat exchanger system for further recovery. The simpler and most cost effective heat recovery system that can be thought for the recuperative burner is given by a double pipe exchanger where the exhaust gas flows in a coaxial tube external to the burner itself.

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Nomenclature

A	section area (mm^2)
D_h	hydraulic diameter (mm)
D_i	exchanger pipe inner diameter (mm)
D_o	exchanger pipe outer diameter (mm)
g	fin crest to insulating wall gap (mm)
h_f	fins height (mm)
l_e	exchanger length (mm)
n_f	fins number (–)
p_w	wetted perimeter (mm)
$\dot{Q}$	rate of heat transfer (kW)
R	thermal resistance (°C/kW)
r_f	fins thickness ratio (–)
T	temperature (°C)
t_b	fin base thickness (mm)
t_c	fin crest thickness (mm)
V_e	heat exchanger pipe volume (mm^3)

Greek Symbols

α	domain angular width (rad)
α_b	angle subtended at the fin base thickness (rad)
α_c	angle subtended at the fin crest thickness (rad)
ΔT_b	bulk temperature difference across the heat exchanger (°C)
ΔT_m	log mean temperature difference (K)
λ	equivalence ratio (–)

Subscripts

e	relative to the heat exchanger wall
in	relative to the inlet section
out	relative to the outlet section
s	relative to the secondary air flow
t	total
x	relative to the exhaust gas flow

Such a solution is not particularly efficient due to the low residence time of the gas in the exchanger and the relatively low wetted area. Nonetheless, considering the industrial constraints of low pay-back time, easy manufacturability, need for low maintenance, resistance to high temperatures and chemically aggressive environments, more complex and thermally efficient solutions would be quickly discarded.

The focus is thus on finned concentric pipes heat exchangers made of silicon-infiltrated silicon carbide (SiSiC). The choice for the material is due to its resistance to high temperature and its good thermal conductivity. The simple geometry offers limited margins for optimization, yet a fine tuning of the geometrical parameters could lead to an optimum balance between the extended wetted areas and the allowable pressure drop across the heat exchanger, usually limited due to technological reasons.

The idea of a recuperative burner is not new and was already widely discussed in review papers in the early eighties [5]. The main concern about these systems is their being prone to larger NO_x formation rates due to the higher flame temperatures that are occurring by pre-heating the combustive agent. In such cases, the enhancement of turbulence or the adoption of staged combustion can help in mitigating NO_x production as discussed in Ref. [6].

More recently, research devoted to burners has focused on flameless combustion, also known as Moderate or Intense Low-oxygen Dilution (MILD) combustion. Flameless combustion essentially consists in the recirculation of a given amount of exhaust gases into the combustion chamber. In this way, by smoothing temperature peaks out, a drastic reduction in NO_x formation is obtained [7]. From an industrial point of view other advantages are a more uniform temperature distribution [8], a better flame stability under certain operating conditions [9], and of course a better heat recovery from exhaust gases. Despite this, MILD combustion has not yet spread in industrial applications due to the additional complexity in the burner design given by the need of an exhaust gas recirculation system.

The literature concerning double pipe heat exchangers is very large, and over the years the focus has been on evaluating the effectiveness of several different means for improving the heat transfer going from, to cite a few, the use of fins of various kinds and shapes [10], swirled flows [11], porous structures [12], and so on. A wide review on the use of extended surfaces, such as fins or pins, in heat exchangers is also given in Ref. [13].

The use of optimization methods in heat exchangers design is also a rather discussed topic in literature. Yet, to the authors knowledge, no optimization application is found relative to double pipe finned heat exchangers. Maybe because of their simplicity and relatively low efficiency that limit their use in practical industrial applications. Among the most recurrently optimized types we find plate-fin heat exchangers [14], shell-and-tube heat exchangers [15], and microchannels heat exchangers [16].

Concerning the optimization problem setup, the works either rely on analytical models of the heat exchangers, or on Computational Fluid Dynamics (CFD) simulations. The variables of course are always given by a set of geometry-related parameters, while the constraints, if any, usually regard the admissible pressure drop. Both single and multi-objective optimizations are found, while the use of genetic optimization algorithms is predominant. The most typical objectives relate to thermal and fluid dynamic aspects of the exchangers: maximization of the heat transfer, the temperature jump, or the Nusselt number, and minimization of the pressure drop, or the friction factor as in Ref. [17] and in Ref. [18]. A few studies also involve objective functions generating from economic considerations, such as operative, maintenance, or material costs [19]. Volume minimization is usually addressed in compact heat exchangers applications [20]. A few works also approach the problem in terms of the second law of thermodynamic, thus focussing on the minimization of the entropy production, or of a modified entropy generation number [21].

Only recently, the first works in which the open source CFD code OpenFOAM has been applied to heat exchangers design problems have appeared in literature, as in Ref. [22] where a typical HVAC application heat exchanger is addressed, even though without including optimization methods. One of the latest extended reviews on the use of CFD in heat exchangers design [23], in fact, shows no trace of that code yet.

In the present paper, we address finned concentric pipes heat exchangers. The heat exchange rate is predicted by means of the open source CFD code OpenFOAM, and maximized using the Nelder and Mead simplex optimization algorithm [24] under pressure drop, compactness, and cost-related constraints. The variables of the optimization include several geometrical parameters, mainly related to the shape of the finned surface. The work, even though originating from an industrial problem of heat recovery in recuperative burners for ceramic kilns, follows a general approach having general validity.